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Precise Laser Incisions, Corrected for Patient Respiration With an Intelligent Aiming System

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Background and Objective: **Patient motion due to respiration and blood flow can negatively affect the precision of a laser incision.**
Study Design/Materials and Methods: **The video image of the surgical field is monitored by a computer system, and trends in the motion are "learned" by the computer. The laser beam is then adjusted to compensate for predicted motion. Occasional erratic motion sometime causes a false prediction. In this event, the prediction is corrected with real-time feedback.**
Results: **Our experience shows that even with occasional false predictions, the motion compensation still gives a better incision. The surgeon always maintains control of the laser. The net effect of the intelligent aiming system is to subtract away nearly all patient motions.**
Conclusion: **Laser surgery can be performed with greater accuracy and reduced unwanted tissue damage with the predictive tracking of motion. Lasers Surg. Med. 20:210–215, 1997.**

Key words: **beam delivery; computer-controlled scanning; laser surgery; motion tracking; robotics**

INTRODUCTION

To use a laser effectively in surgery, one must be concerned with the control and delivery of the laser light. Several innovative delivery and monitor systems are being developed in the Computer-Assisted Surgical Techniques (CAST) program at the Vanderbilt University Medical Center [1–3]. The union of the computer and robotics to assist the surgeon with laser beams presents many new and exciting applications. For instance, the computer is capable of tracking the natural motions of a patient, and the computer can then adjust the direction of the laser to compensate for the motion. The computer can also "subtract" these motions from the video image of the surgical field. Thus creating a still image even when motion is taking place. The tracking software uses a maximum entropy analysis to predict future motion from its recent history. The implementation of tracking to the computer-controlled scanning creates an attractive device to be used with nearly all surgical laser systems.

Machines have been used to assist man throughout history. High technology has produced machines that can perform high-precision tasks at incredible speed. Advanced technology and state-of-the-art electronics are not new to modern medicine. Specific examples of high technology in medicine include X-rays, laser, ultrasound, and magnetic resonance imaging. Not only are these technologies firmly implanted in the

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U.S. medical care system, but medicine embraced these high technologies very early in their development. It stands to reason that high technology will continue to be imported into medicine. At the same time, medicine will motivate and drive the direction of selected technologies.

Most appropriately, consider the history of the surgical laser. Theodore Maiman first achieved lasing in ruby on May 16, 1960 [4]. It was only 18 months later in December 1961 that a prototype ruby laser was used to destroy a retinal tumor in a patient [5]. Leon Goldman, M.D., is often cited as the force to move the laser from ophthalmology to non-ophthalmologic medicine [6,7]. He established a medical laser laboratory in 1962 at the University of Cincinnati. Laser surgery equipment was already in the marketplace in 1965, less than 5 years after the first working laser was developed in a physics laboratory.

Research continues toward the development of improved applications of the laser. One area of investigation is the finer control of the laser. This would lead to increased precision in ablation when compared to hand-held probes and micromanipulators. This finer control can be achieved with the aid of computers. A computer-directed laser beam would offer greater precision and flexibility in the shape and size of incision. The currently available Hexascan™ has shown this to be true; however, the Hexascan™ is limited in that only hexagonal excisions can be made [8–10]. In addition, Sharplan has introduced two handpieces: the Swiftlase™ moves the CO_2 laser beam in a rosette pattern, and the Silk Touch™ handpiece moves the laser beam in a spiral, to avoid the "hot spot" created at the center of the rosette.

The development of handpieces to move the laser beam and computer-controlled scanning devices is progressing at a fast pace. Silver Creek has a handpiece for the CO_2 laser that produces a spiral pattern, similar to the Sharplan handpiece. In addition, some of the new handpieces allow for greater flexiability in the pattern scanned. Coherent is marketing the CPG or Computer Pattern Generator, capable of moving the laser beam in many different pre-programmed patterns. The beam from this scanner is not focussed, but collimated with a small cross section, so the scanned patterned is always "in-focus."

COMPUTER-ASSISTED SURGERY TECHNIQUES

At the inception, the CAST system replaced the joy stick of the micro-manipulator on a surgical microscope with servos and computer direction (see Fig. 1) [1–3]. The image through the surgical microscope is inserted on the computer screen. On the same screen, the surgeon then draws the line or pattern that he or she wishes to incise. Using the computer together with the laser, the surgeon is capable of making an incision with minimal lateral damage and extreme precision.

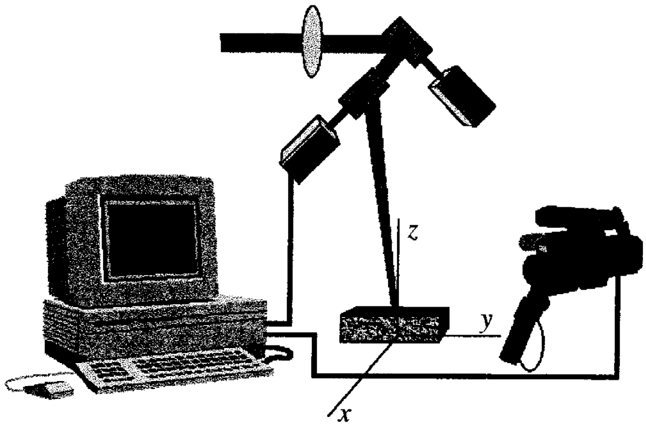

Fig. 1. Diagram of the basic concept behind the Computer-Assisted Surgical Techniques (CAST) system. The direction of the laser beam is controlled by two mirrors on servos. The servos are controlled by a computer system. The ablation target is imaged with a video camera, and those images are displayed, real time, on the computer screen. The x, y, and z axis system is shown on this figure for clarity in text discussions.

The computer-controlled scanning laser beam must track with patient motions. The main thrust of this research initiative is the addition of tracking to the laser scanning and the subtraction of motion from the image of the surgical field.

MATERIALS AND METHODS

The details of the CAST system can be found in previous publications [1–3]. With the CAST system, the surgical field is monitored by a video camera (MKC-301A, Ikegami, Tokyo, Japan). The video signal is input into a Macintosh computer (PowerMac 7100 AV) with a built-in video card (Apple Computer Co., Cupertino, CA). The tissue is tagged with one or more pins with green heads. These pins are readily identified by the computer and serve as fiducial points. The center of the pins is computed from the image pixels. The resolution of position is therefore slightly greater than the pixel image size. Since the surgical field is viewed through a surgical microscope (OPMI 1, Zeiss, Germany) for microsurgery (up to 25× magnifi-

cation, 400 mm objective lens), and the video camera also images through the microscope, a single pixel is approximately 20 μm. This is sufficient resolution for a laser beam diameter of 200 μm or more.

The Macintosh is programmed to locate a green spot from a video image with a combination of Apple Script (Apple Computer Co., Cupertino, CA), LabView 2.0 (National Instruments, Austin, TX), and assembled C code (C++, Symantek Corp., Cupertino, CA). This process is one of the rate-limiting steps. Several years ago we were concerned about the speed of the computer to handle color video images at a 30-Hz rate. The newest computers, the Power Macs with the RISC processor, are sufficiently fast to process the images at 30 Hz.

The motions of the pins are monitored for a short time (approximately 30 s). In all the studies presented here, a single fiducial point was used. The next-generation systems will use more points. The x-y motion of the pin is computed and recorded by the computer. These coordinates will be analyzed with the Maximum Entropy Method (MEM) to predict future motion.

The MEM tracks motions that are periodic or follow a functional trend (a smoothly varying first and second time derivative of the displacement). Any motion that is slow compared to the video frame time (16 ms) can be tracked with MEM. In otolaryngology–head and neck surgery, the patient motions are primarily due to breathing, pulse, and heart beat. All of these motions are slow compared to 16 ms. In fact, there are very few physiological motions that are too fast to track with MEM. Examples of the few motions too fast to track would include spasmodic tremors and motions of the eye.

RESULTS

The motion of the chest on a normal, awake male volunteer was imaged, and the motion as well as the tracking is shown in Figure 2. For presentation purposes, the motion along only one axis is shown. This axis was chosen to represent most of the chest motion. Instead of using a pin as a fiducial point, a green dot was fixed to the chest with rubber cement.

As a limiting case, we show the tracking of the abduction and adduction of the vocal folds from an anesthetized canine in Figure 3. Again, the motion along one axis is shown. The axis was selected to be parallel to the major motion. The

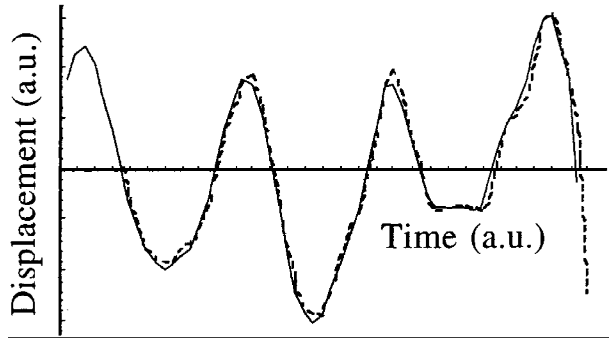

Fig. 2. The recorded motion of a chest during respiration. The solid line is the measured displacement. The gray, dashed line is the predicted motion using the maximum entropy method (MEM). The prediction correlates quite well with the measured displacement.

tracking missed one point during an irregular respiration pattern. The tracking recovered at the next point and continued to track the motion with minimal deviations.

DISCUSSION

After the motion is tracked for some initial time, the computer will start to predict the motion, make corrections and input the actual motion. The predictions will be adjusted for the actual motion. We have tried this technique to follow the breathing from a person at rest and the abduction and adduction of the vocal folds from a canine larynx. The dog was anesthetized by injection and the vocal folds were videotaped with an endoscopic camera. The coordinates of the fiducial points were then analyzed with the MEM and the motion was predicted. After each prediction, the actual motion was added to the MEM calculation. As shown in Figures 2–3, we have the motion and the predicted motion. Excellent agreement is seen. In Figure 3, the fourth breath cycle was shorter than normal. Still, the predictive analysis was able to adapt after one missed prediction.

One could look at the one "missed" point of the prediction and might conclude that the system does not work. That is unfair. This is the first prediction ever made, and it is remarkably accurate without any refinements. Also, the one missed point is far superior to no tracking, where the majority of the points would "miss." We note that a scanner without tracking would simply move along the x-axis in Figures 2 and 3. It is also important that the tracking does not become "lost" after missing a single point and fail to correct itself quickly.

The ability to predict the motion as shown in

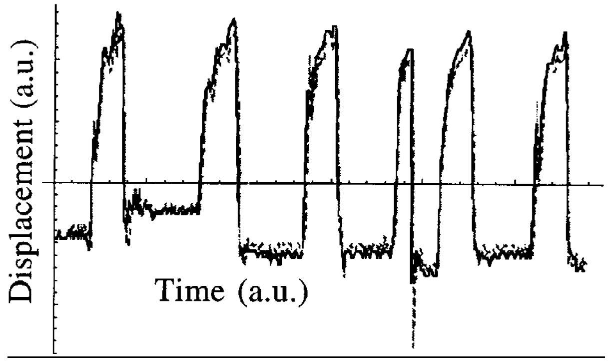

Fig. 3. The recorded motion of the canine vocal fold. The solid line is the measured motion. The dashed line is the predicted motion using the maximum entropy method (MEM). The large overshoot in the fourth cycle is due to the faster than normal adduction of the vocal folds. The feedback quickly corrects the problem.

Figures 2 and 3 is useless to a surgeon in the form of a plot. The motion prediction must be used to redirect a laser or surgical tool or to subtract the motion from the real-time video image of the surgical field. In this first phase of the research, we used the motion predictions to adjust the video image on the computer monitor. If the adjustment is done correctly, the motions of the tissue do not show on the video monitor.

Thus far, all the motion has been from the moving of a single fiducial point. It is then assumed that the object does not change shape. Instead, the object is assumed to translate uniformly. In reality, the shape is often not preserved. Also, objects can rotate. We will increase the monitoring to three fiducial points per image. The motion in the x and y directions can then be the sum of translations, rotations, and linear distortions (a simple spring model of tissue). If this homogeneous linear model is not sufficient to subtract the motions, more fiducial points and higher-order equations can be used to describe the motion. It will be clear from the video image if the motion is being subtracted appropriately. Jumping and transient distortions in the image will result if the motions are subtracted inappropriately.

We anticipate that three to five fiducial points will be sufficient to describe the motion. Three fiducial points will provide six data points (changes in the x and y position for each point). We can use this information to determine five changes in the tissue: x translation, y translation, rotation, stretch of the x direction, and stretch of the y direction. This may not perfectly describe the motion. The use of additional fiducial points would permit nonuniform stretch in the x or y direction. There is a limit to the number of fiducial points and the complexity of the motion. We must have all the calculations completed in 16 ms to keep the system real-time. We expect the new Power Mac computers to be sufficiently fast to make any reasonable calculation. In addition, we have an optimized compiler for the computer and each step of the programming is being carefully optimized for speed.

We are not concerned with motions in the z direction (toward and away from the observer) at this point. The surgical microscope is routinely used with a 400-mm objective lens. We use 400-mm objective lenses to image through laryngoscopes. The very large f number (f $\geq$ 20) of the microscanner and the long wavelength of a CO_2 laser translates into a large depth of field. Objects can displace nearly 1 cm in the z direction and stay in focus with the microscanner. Motion in the z direction might become important in other systems. We feel that it is a significant problem, but one that can be solved.

Since we are limiting our system to the commonly used surgical microscope and the most common surgical laser, we can fortunately ignore motions in the z direction. That does not mean the problem is difficult to solve. There are several methods on the market that keep the object in focus along the z-axis. Coherent has build a handpiece that delivers collimated laser beams with small cross sections. This eliminates the focal distance problem. The problem has also been solved on most new automatic 35-mm cameras. In fact, Canon and Nikon also have predictive auto-focus or auto-focus tracking on their professional cameras.

Other Tracking Systems

We have considered many types of tracking systems before selecting the MEM. Tracking is used in various fields. In the field of biomechanics, computers assist in the tracking of human motion [11]. These tracking programs are analytical, providing an analysis of rotation of limbs and force. The programs are not optimized for prediction. Yet, we do follow the research to learn of new methods of digitizing images and target identification. For instance, a “TrakEye” system is used to film a horse running [12]. It digitizes the images and monitors the motion of the fetlock. The system tracks amazingly well, but does not operate in a real-time mode.

Target tracking and real-time adjustments are investigated for a wide range of applications in ophthalmology. In a very recent study, a laser Doppler velocimeter was used to stabilize the eye for hemodynamic measurements [13]. The motions of the eye are fast and quasi-random. So, these systems use fast "cameras" and fast processors to measure the motion and compensate for the motion after the fact. There is no prediction involved. The system we are proposing uses the MEM to predict motion from the recent history. Since many of the physiological motions are quasi-periodic, we will utilize the predictive capabilities of the MEM. This permits us to use slower cameras. These cost concerns are important for potential commercial applications.

The Department of Defense funds a large amount of tracking research. There are two purposes behind their funding. They are searching for ways to track the jitter of communication satellites to optimize information transfer. They are also searching for ways to track targets to increase weapon effectiveness. The jitter in the motion of a communication satellite comes from many different sources, such as gyroscopes, servos, the earth's gravitational field, elastic forces in tension and bending, solar and lunar gravity, solar radiation, and micrometeroid impacts, just to name a few [14]. Systems developed for pointing, acquisition, and tracking (PAT) attempt to minimize the jitter effects [14,15]. Like the eye motion, the satellite jitter is fast, compared to the sampling time, and random. The PAT systems measure the motion and compensate.

A recent publication compared three different methods of target tracking [16]. A comparison is made between the Simple Threshold (ST) Method, the Truncated Sequential Probability Ratio Test (SPRT), and the Retinal Motion Detector (RMD). The RMD is an algorithm that is loosely modeled after biology [17,18]. The technique is interesting and is being considered in detail. The tests reported by the authors indicate that the RMD works as well as the ST method or SPRT (but not better) in good lighting conditions. However, in conditions of low light, luminance gradients and contrast reversals, the RMD outperformed the other methods. In general, the lighting in a surgical field is very good. Nevertheless, we might be able to adapt some of the RMD algorithm into the MEM system.

One final remark concerns a study of the control strategies used to direct the hand to intercept a moving target [19]. In experiments performed with humans and an object moving at a constant velocity, a latency period was measured between the appearance of the target and the motion of the hand. The latency period was modeled as the sum of two components: a fixed processing time, and the time taken for target motion to be detected. If the target moved faster, the time to detect motion decreased and so did the latency period. The hand and eye are relatively good at tracking moving targets. This research suggests a predictive algorithm is used to control the hand after the initial velocity is determined. If there is a random motion of the target, the initial motion of the hand was independent of the target velocity. However, after a time period elapsed for the brain to compute the target velocity, the hand would increase its velocity. The peak hand velocity depended upon the target velocity and was similar for all subjects. This again suggests predictive control of the hand. The time at which the peak occurred varied substantially among the subjects. This suggests some "guessing" or other variation in the control mechanism.

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